DIRECT OBSERVATION OF SUPERHEATING AND SUPERCOOLING OF VORTEX MATTER

A current question of fundamental interest concerns whether a vortex solid-liquid transition exists in type-II superconductors [1]. In addition to providing a possible model system for melting and freezing, vortex matter offers unprecedented opportunities to study the effects of quenched disorder on phase transitions. The peak effect, where the critical current exhibits a peak rather than decreasing monotonically with increasing temperature, has been found to occur at the same temperature as a magnetization jump, which suggests a melting of the vortex lattice. However, there has been no direct structural evidence indicating whether there is indeed an underlying phase transition, and if so, whether it is solid-to-solid, solid-to-liquid, or even liquid-to-liquid in origin. Moreover, since quenched disorder is known to have important consequences for phase transitions, whether a solid-liquid transition can occur when random pinning is effective has broad implications in condensed matter physics.

Here we report the first observation of a striking history dependence of the structure function of vortex matter in the peak effect regime in a Nb single crystal, using SANS combined with simultaneous magnetic susceptibility measurements [2]. Metastable supercooled vortex liquid and superheated vortex solid phases have been observed, providing direct structural evidence for a first-order vortex solid-liquid transition associated with the peak effect.

Measurements were performed on a Nb single crystal, with the incident neutron beam nominally along the cylindrical axis which coincides with the three-fold symmetric <111> crystallographic direction. A superconducting magnet applies a dc magnetic field along the same direction. The peak-effect regime is determined *in situ* by measuring the characteristic dip in the temperature dependence of the real-part of the ac magnetic susceptibility χ', as shown in Fig. 1(a) for H = 3.75 kOe [2]. The pronounced diamagnetic dip in χ'(T) of the *ac* susceptibility corresponds to a strong peak effect in the critical current. The onset, the peak, and the end of the peak effect are denoted by $T_o(H)$, $T_p(H)$, and $T_{c2}(H)$, respectively. Figure 1(b) shows the window of the experiment.

For each (T,H), we measure the SANS patterns for different thermal paths. At sufficiently low temperatures the SANS images show sharp Bragg peaks with six-fold symmetry, independently of the thermal history. An example is shown in the inset of Fig. 1(b) for H = 3.75 kOe and T = 3.50 K. However, the vortex pattern starts to show striking history dependence as the peak-effect regime is approached. We define the field-cooled (FC) state as when the sample is cooled to the target temperature in a magnetic field, while the zero-field-cooled (ZFC) state is reached by cooling the sample in zero field to the target temperature and then increasing the magnetic field to the desired value. For a field-cooled-warming (FC-W) state, the system is cooled in-field to a low temperature (≈ 2 K), then warmed back to the final temperature.

For the FC path, the vortex patterns show nearly isotropic rings for $T_p < T < T_{c2}$ and broad Bragg spots for $T < T_p$. In contrast, for the ZFC and the FC-W paths, sharp Bragg spots are observed for all temperatures up to T_{c2}. Shown in the top panel of Fig. 2 are

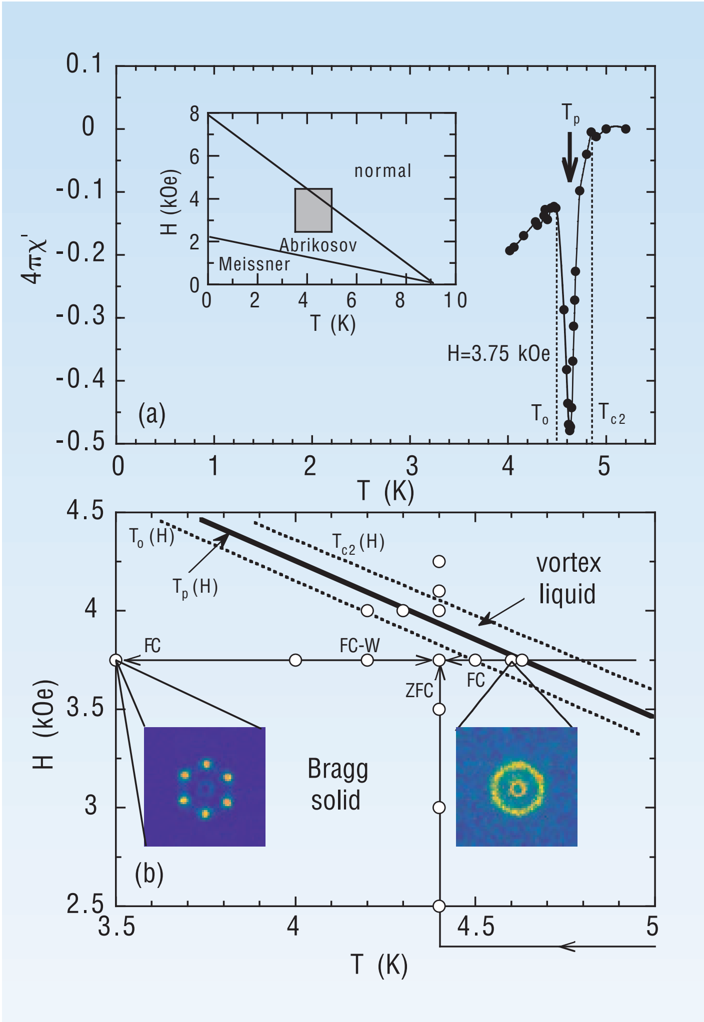

FIGURE 1. Peak effect and (*H-T*) phase diagram of Nb. a) ac magnetic susceptibility for H_{dc} = 3.75 kOe (field-cooled). H_{ac} = 3.3 Oe and 1 kHz. Inset: global *H-T* phase diagram for the Nb crystal used in this study. (b) Expanded view of the *H-T* phase diagram (shaded box in a). Two observed SANS images of the field-cooled vortex states are shown.

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the ZFC and FC images at (3.75 kOe, 4.40 K), which is just below T_o(3.75 kOe) = 4.50 K. The images in the mid panel are for (4.00 kOe, 4.40 K), which is 0.10 K above T_p(4.0 kOe) = 4.30 K. The intensities at the radial maximum for the mid panel SANS data are plotted in the lower panel. The sharp Bragg spots for the ZFC state indicate a vortex lattice with long-range-order (LRO), while the very broad spots for the FC state signify a disordered phase with short-range-order.

The observed hysteresis suggests a first-order vortex solid-liquid (or glass) transition. A controversial issue is the location of the underlying equilibrium phase transition to the position of the peak effect. One interpretation places the conjectured vortex solid-liquid transition T_m at T_p, consistent with the recent experiments in YBCO. Another widely held view is based on the classical Lindemann criterion which would place T_m at $T_{c2}(H)$ for Nb, provided the vortex-lattice elastic moduli remain well-behaved. In this scenario, the FC disordered phase seen here (as well as in [3,4]) is a supercooled liquid and the thermodynamic ground state is an ordered solid across the entire peak-effect regime. The third scenario places T_m at or below the onset of the peak effect.

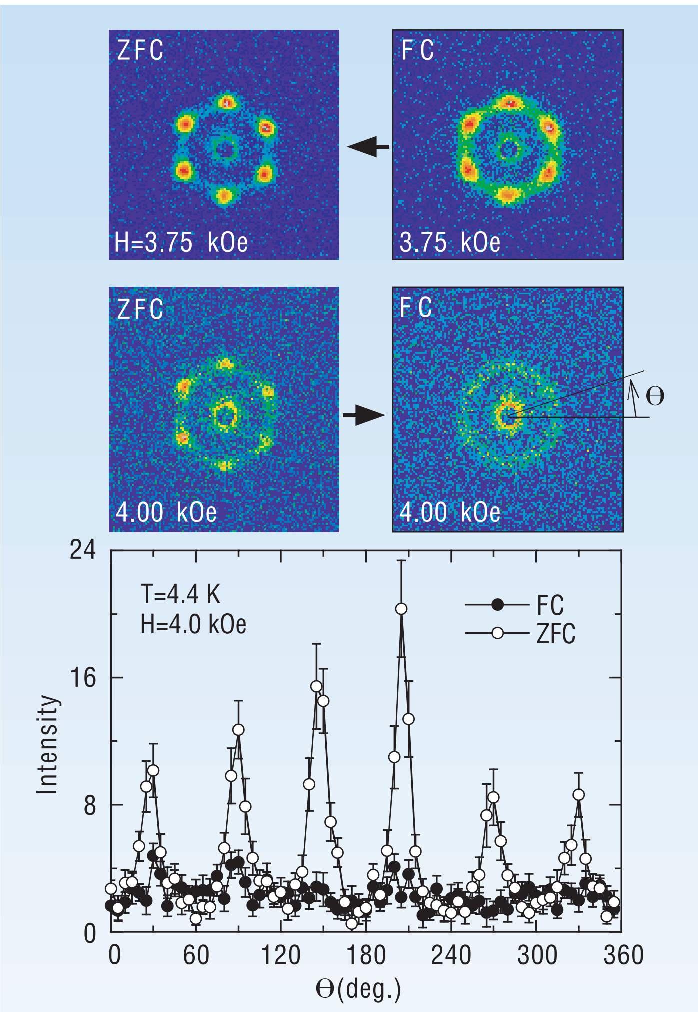

FIGURE 2. History-dependent SANS patterns at 4.40 K. The SANS images of the ZFC and FC vortex states for *H* = 3.75 kOe (top panel: below the onset of the peak effect) and *H* = 4.00 kOe (mid panel: near the upper end of the peak-effect regime). The thick arrows indicate how the SANS images evolve after applying a small ac magnetic field. The lower panel shows the intensity data at the radial maximum as a function of the azimuthal angle for the ZFC and FC SANS data (*H* = 4 kOe).

To experimentally determine the ground state and approximate value of T_m, the susceptibility coil was used to shake the vortex assembly, using SANS to observe how the vortex structure evolves. The data show that above T_p the Bragg peaks start to disappear within the first 10^2 sec of the shaking experiment, demonstrating that the equilibrium state is disordered. Similiarly, the FC disordered states for $T < T_p$ are metastable and the ordered ZFC state is the ground state, opposite to that for $T > T_p$. In the $T < T_p$ regime, though, the metastability is obviously stronger since a much larger ac field is needed to change the metastable state.

We conclude that for $T > T_p$ the ordered ZFC vortex lattice is a superheated state and the ground state of the vortex system is a disordered vortex liquid, while for $T < T_p$ the ground state is a vortex Bragg solid and the disordered FC state is a supercooled vortex liquid. A thermodynamic phase transition must therefore have taken place, with $T_m \approx T_p$. These results also imply the absence of superheating in conventional transport experiments with a large drive current, which solves a longstanding puzzle in which the history dependence of the nonlinear resistance always vanishes at $T_p(H)$; only with extremely low drive currents may one then observe the subtle effects of superheating in transport.

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